LONG-TERM MONITORING OF A HEATHLAND CONSERVATION PROJECT: A TALE OF TWELVE QUADRATS

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A simple, long-term (39-year), monitoring program is described, designed to assess the success of lowland heathland conservation management at Thurstaston Common SSSI on Wirral. This was carried out largely by volunteers with minimal equipment. We outline the process of moving the data from field-based collection sheets and simple Excel worksheets to a digital platform, where routine graphical and statistical analyses can be performed easily. We present some graphical outputs of change for selected species, tree height, and cover-weighted fertility index based on Ellenberg's N values. Multivariate analysis separated sites into three categories based on an internally-generated traffic-light system. The results show that for the most part the current management (primarily grazing and tree removal) is maintaining the heath communities, although concerns were identified about an overall reduction in lichens, and in a few quadrats an increase in species indicative of fertile conditions. The derived results provide useful information to help the National Trust managers plan their activities. It is hoped that this paper might encourage other volunteer groups to consolidate their data digitally and perform similar analyses.

INTRODUCTION

This paper charts the recent progress of a small, relatively long-term monitoring scheme set up to assess the conservation value of a small heathland reserve, Thurstaston Common SSSI (SJ245851) on the Wirral Peninsula and to assess change brought about by management and successional change. We suspect that this sort of monitoring scheme is similar to many others done routinely by local conservation groups run by volunteers, often coordinated by NGOs such as Wildlife Trusts. We offer up our experience in developing an analytical framework for the collected data to show what can be achieved with modern graphical/statistical methods and to encourage others to look at their monitoring datasets more critically, and perhaps provide better outputs. As the objective is to provide management guidance and needs to be easily understood by non-specialists, in this paper therefore, we concentrate mainly on graphical outputs.

Issues with conserving heathland

Lowland heaths are cultural landscapes, created and maintained by human activities (Gimingham, 1972, 1992; Webb, 1986; Diemont *et al*., 2013); ecologically, they are described as plagio-climax systems or arrested seres (Marrs, 1988) where succession to woodland is prevented by a combination of burning, cutting, grazing and turf-removal (Gimingham, 1972, 1992; Webb, 2008; Diemont & Linthorst, 1989). These management techniques helped maintain very infertile, acid soils, especially on sandy substrates (Gough & Marrs, 1990; Marrs, 1993).

The vegetation dynamics involved in heathland management are quite complex and can be viewed from several different angles (Figure 1a). Central to heathland management is the *Calluna vulgaris* life-history regeneration cycle (bold-line cycle, Figure 1a) first described by Watt (1947, 1955) and re-defined as a regeneration cycle by Miles (1979). *C. vulgaris*, the dominant species in most British lowland heaths goes through a 4-phase, age-dependent cycle (phases: pioneer > building > mature > degenerate). Maintenance of the heaths can be described as needing a "goldilocks" state, i.e., the management has to be "just right, neither too much, nor too little" (Davies *et al*., 2021). If the management is too intense the vegetation will change into grassland (to left-hand side, Figure 1a) and if there is not enough management, succession to woodland will proceed (to right-hand side, Figure 1a). The manager must, therefore, (a) manage the vegetation to maintain the *C. vulgaris* regeneration-cycle (*sensu* Miles, 1979) working with endogenous processes (Marrs, 1986), and (b) prevent a movement towards either woodland or grassland. There is an additional regeneration pathway between mature/degenerate phases in some heaths under relatively moist conditions in cool wet parts of upland Britain (MacDonald *et al*., 1995). Where this occurs, the older stems "layer" vegetatively within the litter layer. With a relatively-low rainfall of approximately 600-700 mm (Anon, 2021) layering is unlikely to occur at Thurstaston Common except in areas that can be maintained in a waterlogged condition. Added to this is the potential for catastrophic death events caused by exogenous processes. This has been documented after Heather Beetle (*Lochmaea suturalis* Thomson) attack or climatic extremes, e.g., drought or cold temperatures (Marrs, 1986), or after severe wildfire. When this occurs, late-building and mature stage *C. vulgaris* can be killed off, sometimes over very large areas, initiating either regeneration of pioneer *C. vulgaris* from the seedbank, or ingress of tree seedlings or transition to grassland (Figure 1b, de Smidt, 1977; Marrs, 1986). Where this occurs, there is the opportunity to move away from a *C. vulgaris*-dominated community to a different one that does not necessarily meet the conservation objectives of maintaining heathland plant communities.

On top of these management issues, there are other pressures that are likely to affect plant species responses, for example atmospheric inputs of nitrogen which cause eutrophication, detected in the uplands and across the UK more generally (Smart *et al*., 2003; Mitchell *et al*., 2017, 2018). Moreover, there is also the changing impacts of soil acidification as a result of high atmospheric SO_2 concentrations which were prevalent in the middle of the twentieth century. However, SO_2 concentrations have declined since the 1980s and there is evidence that soils are becoming less acidic (Mitchell *et al.* 2017). A simple way to assess such changes through time is to convert the species data into a weighted index that reflects both the abundance (here, species cover) and species' functional traits (Pakeman, 2004). Here, we used the comparative responses 'functional traits' derived for each species by Ellenberg *et al*. (1991) for four environmental variables, i.e.:

1. Light - Ellenberg L, a value between 0 (deep shade) and 9 (full light), here we would hope for an increase in the index, maintaining open conditions.
2. Moisture - Ellenberg F (from the German Feuchtigkeit), a value between 0 (extreme dryness) and 9 (submerged), here we would hope that an index value for the wetter sites, i.e., those areas on a clay layer over sand, will be maintained and even increase.
3. Reaction - Ellenberg R (= acidity), a value between 1 (extreme acidity) and 9 (basic soils), here we would hope for maintenance of relatively acidic conditions.
4. Fertility - Ellenberg N, a value between 1 (extreme infertility) and 9 (extremely rich soils), here we would hope for maintenance of relatively infertile conditions and any increase would be seen as problematic.

Thurstaston Common SSSI

Thurstaston Common (71.6 ha) was designated as one of the first SsSSI in 1954. It is the largest and best remaining example of a lowland heath in Merseyside. It is owned and managed jointly by the National Trust and Wirral Metropolitan Borough Council. The soils are predominantly podzols overlying Triassic sandstone. The heath vegetation is a mixture of wet-heath, dry-heath, acidic marshy grassland and birch-oak woodland. Most of the heath vegetation is dominated by *C. vulgaris* with *Erica cinerea* and *Ulex gallii* in the drier areas and *Erica tetralix* and *Molinia caerulea* in the wetter areas of heathland. Some parts of the Common contain good examples of the *C. vulgaris*-*U. gallii* (H8) NVC community (Rodwell, 1992). The open heathland is being invaded by *Betula* spp., (*B. pendula* and *B. pubescens*), *Quercus* spp. *Pinus nigra* and *Pinus sylvestris*. The site is, therefore, a good example of a heathland site where there is a constant threat of succession to woodland. There is also a very high visitor use of this site by walkers with, and without, dogs. There are frequent instances of wildfire, some accidental but often set by vandals. The SSSI was scored as 100% in the unfavourable-recovering class by Natural England at the last assessment in 2011 (Anon, 2020). Monitoring the species composition of the heathlands helps to assess whether the management applied is working, or not.

This approach is effectively an adaptive management one, combining best-available knowledge (Holling, 1978). This approach had been criticized as having the potential to do more harm than good (Pullin and Knight, 2009), but risks are reduced as the knowledge-base improves for each conservation situation (Sutherland & Wordley, 2018). This monitoring scheme should assist in these deliberations.

History of the monitoring scheme and management history

The monitoring scheme was originally set up by Phillip Rothwell of the Nature Conservancy Council (NCC, now Natural England) in 1982 with just five quadrats, to provide a baseline to assess vegetation change at a time when sheep grazing was being introduced under a Section 15 Agreement, Countryside Act (1968) between the National Trust (NT), NCC and the late Henry Rogers, the then NT Tenant of Benty Farm. There is anecdotal evidence of grazing having happened on the Common pre-World War II, but no details are available. One of us (AB) became involved in monitoring the original plots in 1984 and later extended their coverage. Information from the monitoring was used to inform a management plan prepared for Royden Park and Thurstaston Common in 1987 and 1994. The initial five quadrats were extended to nine in 1984, 10 in 1988, 11 in 1989 and to 12 in 1990. From 1992, at the request of the National Trust, sampling has been performed by a volunteer team from Wirral Wildlife, a local group of the Cheshire Wildlife Trust, led by Dr Hilary Ash.

The location of the quadrats is shown in Figure 2. Data were collected from all available quadrats in all but three years between 1982 and 2020; the exceptions were 1990 (eight quadrats sampled), 1991 (three quadrats sampled) and 2005 (11 quadrats sampled). There is, therefore, as of 2020, an almost complete 39-year record of vegetation composition change in these quadrats, i.e., almost 57% of the life-span of the SSSI.

The Common does not appear to have been grazed regularly between the end of World War II and the establishment of three paddocks and introduction of sheep for conservation in 1982/83. Initially, grazing was by Welsh Mountain sheep, part of the National Trust Benty Farm tenant's flock. The National Trust introduced Herdwick sheep in 1993 and subsequently Hebridean sheep, but worrying by dogs was an increasing problem. From 2008, some cattle grazed with the sheep, and from 2011 only cattle have been used (6-7 Galloway heifers, May-September annually). Quadrats 7, 8, 11 and 12 are on dry heath in Grazing Paddock 3. Quadrats 1, 2, 3, and 9 are on ungrazed, dry heathland. Quadrat 12 had a wooden fence round it between 1990 to 2008 to assess the effects of excluding grazing animals. When the fence was removed a large *P. sylvestris* tree which was inside the fence, but just outside the quadrat, was left. Quadrats 4, 5 and 6 are on damp heath in Grazing Paddocks 1 and 2. Quadrat 10 is on ungrazed, damp heathland, but this has dried out considerably since 1982. Drying out of the damp heathland is a major problem on this site, and the National Trust installed bunds around the main damp areas in Paddock 1 in the winter of 2015-2016 to try to re-wet the area.

Severe Heather Beetle outbreaks attacked the *C. vulgaris* in 1987-88, 1999-2000, and a smaller outbreak in 2015. Managed fires were carried out within grazing paddock 3 in February 1989 which included Quadrat 7 and a further two areas of un-grazed dry heathland in March 1996, one of which included Quadrat 3. Although successful in regenerating the *Calluna* the practice has not been used again on advice from the then Nature Conservancy Council. Quadrat 12 was established in 1990 with half the quadrat falling within the 1989 burn site. In recent years, other management strategies have been tried in small patches, to rejuvenate the *C. vulgaris* and reduce fire risk. In Paddock 2 a small area was topsoil-stripped in 2014, leading to good regeneration of *E. tetralix*, but this area has not been monitored closely. In Paddock 3 on dry heathland, two contiguous patches of degenerate *C. vulgaris* were closely-mown using a large flail mower in the winters of 2014-5 and 2015-16; dwarf shrubs were cut to ground level and all brash raked off. The second patch included Quadrat 7.

Drought occurs occasionally in Wirral, noticeably in the in summers of 1996, 1997, 2003, 2011 and 2018. This reduced the bryophyte cover. Young *Betula* spp. and *P. sylvestris* seedlings/saplings are removed from some part of the National Trust holding each year. *U. europaeus* is cut back periodically in places e.g. in and around Quadrat 6 in the winter of 2017-18.

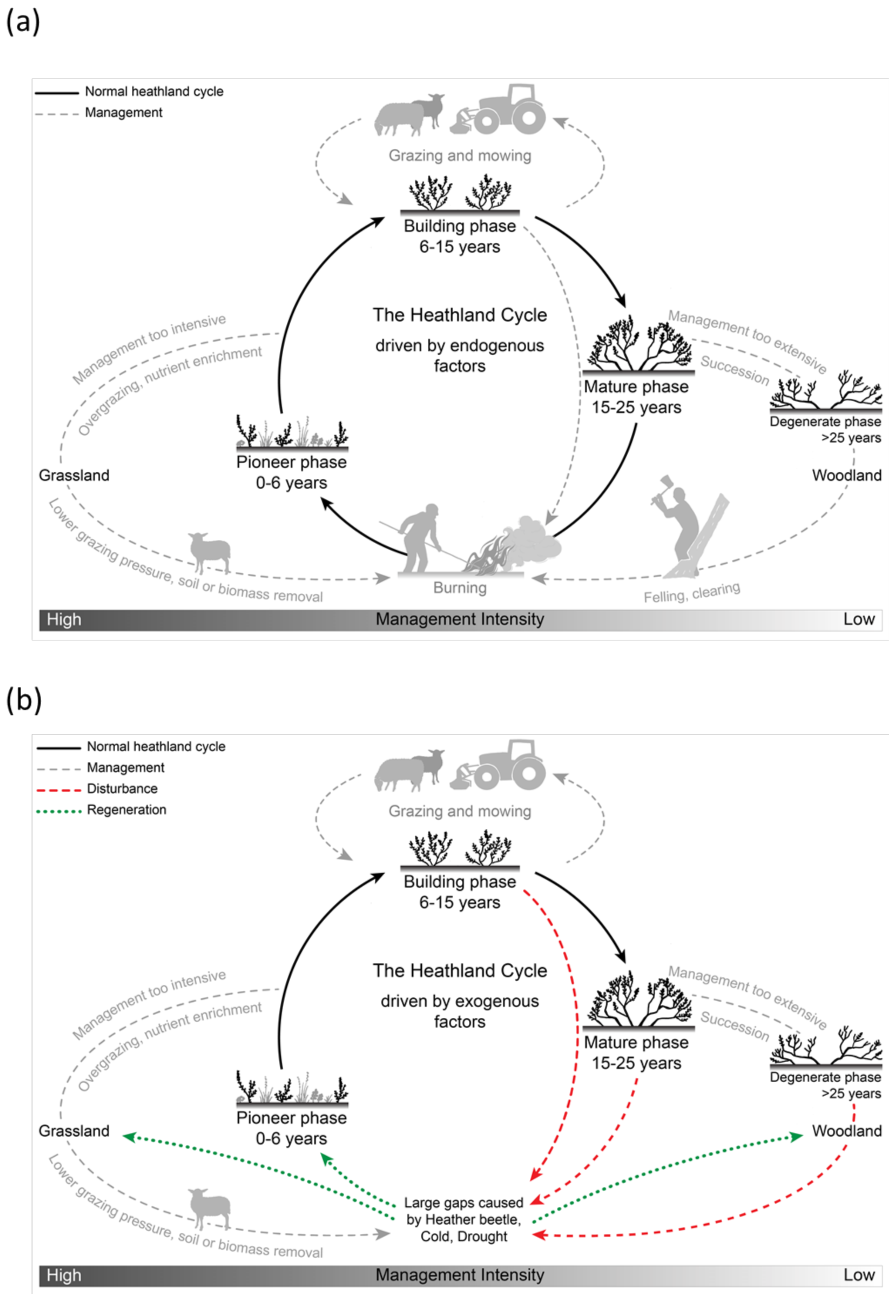

FIGURE 1. Illustration of the modified *Calluna vulgaris*-cycle (Watt, 1947, 1955) to accommodate changes within the wider landscape: (a) the basic endogenous cycle driven mainly by the *C. vulgaris* life-cycle illustrating potential relationships with management intensity and how applied management can be used, and (b) the exogenous cycle where *C. vulgaris* is killed by external factors (red arrows) such as Heather Beetle, drought or extreme cold and regeneration can follow any one of the three green arrows (Marrs, 1986, 1988). [After Davies *et al*., 2021; extended and modified by Dr Dagmar Dorothea Egelkraut].

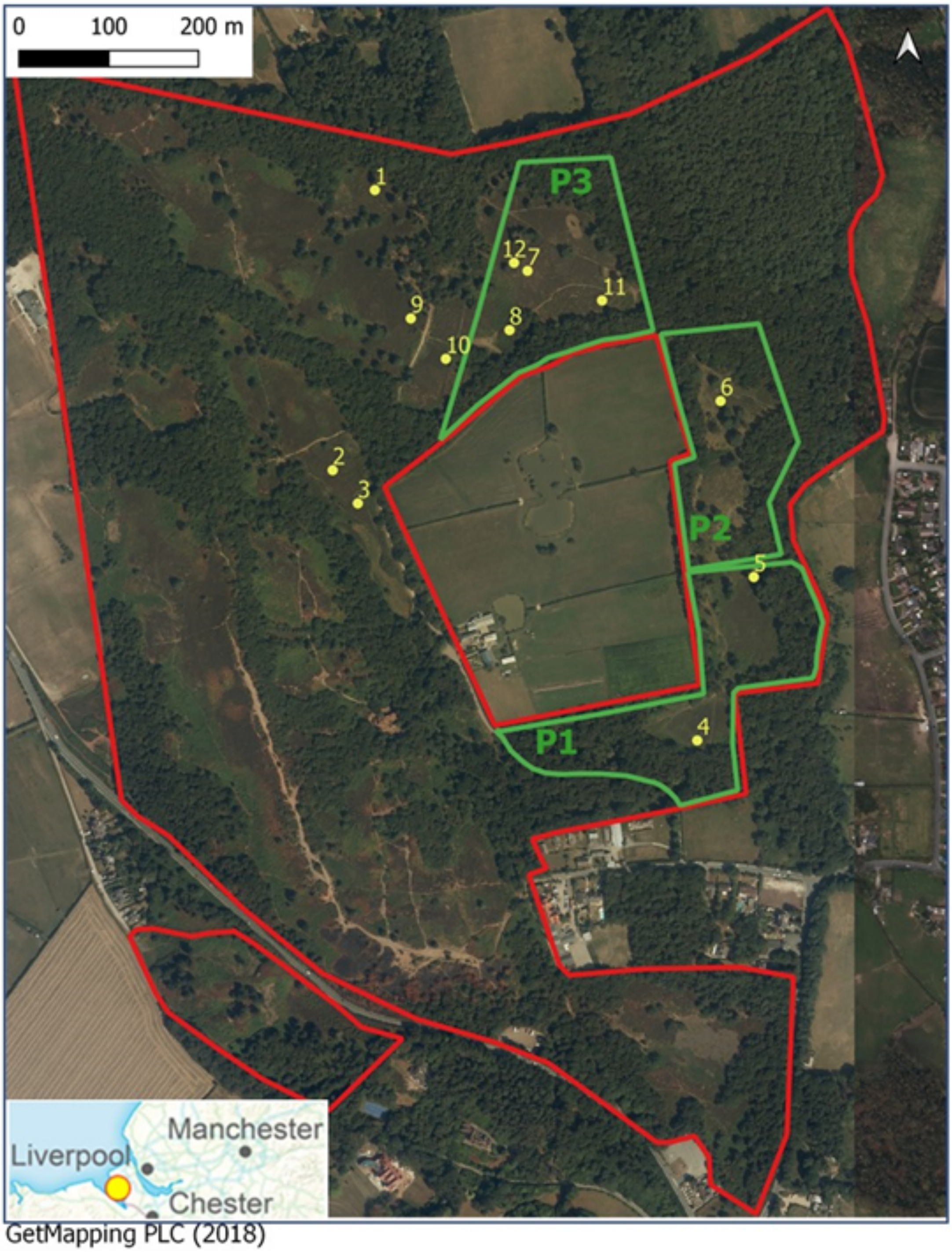

FIGURE 2. Location map of the twelve quadrats on Thurstaston Common, Wirral, UK. The three grazing paddocks (P1, P2 and P3) are denoted in green, the quadrat locations are located by yellow number and the main SSSI boundaries are in red.

Field methods

All quadrats are 5 m x 5m (25 m^2), which is larger (x6.25) than the recommend minimum sampling area (2m x 2m = 4 m^2) for heathlands and grasslands in the National Vegetation Classification (Rodwell, 1991, 1992). Each quadrat is marked by short, metal rods at each corner and hence are invisible to the general public. They are located by a combination of GPS co-ordinates, metal detector, field notes (updated yearly), photographs, and experience. In order to provide consistency through time, strenuous efforts were made to maintain a continuity of surveyors between years, whilst at the same time bringing in enough new people to avoid problems if a key person drops out. Once located, canes are put at each corner and surveyors tape tied to them while the quadrat is recorded, then removed immediately.

Within each quadrat, plant cover is estimated to the nearest 5%. Species with low cover, <5%, are estimated to nearest 1%. Species with less than 1% cover are recorded as present. For the dwarf shrubs (*C. vulgaris, Erica* spp. and *Ulex* spp.), records are also made of average height (to nearest 10 cm) and scored on a three-point vigour scale (V = Vigorous, I = Intermediate, M= Moribund). Training new recorders is undertaken in the field, with at least two experienced recorders doing the training. The cover estimates are made by each person, then compared, and an agreed figure recorded.

The field records were made on paper using a standardized form, originally designed in a logical manner for ease of use in the field by the volunteer recorders. The records are sent to the NT with a copy retained by Wirral Wildlife. Until 2020, all pre-2011 were on paper and post-2011 onwards were held digitally in EXCEL worksheets which were a reproduction of the format of the field data collecting sheets (Supplementary Appendix: Table S1).

Creation of a new workable database

In late 2019, it was decided to consolidate all records and prepare a database which could be used for basic statistical analysis. We started with the data that had already been transferred into digital form (2011-2019). Immediately on inspection, it was apparent that the data in field-collected form needed considerable manipulation to prepare it for any form of statistical calculation. At this point, it was only possible to do simple within-year summaries of individual variables, and difficulties arose specifically because:

1. The quadrats were input as columns and species as rows, most statistical packages require that the variables (here species) be columns.
2. Mixed cover (quantitative) and VIM (qualitative data).

Part of the clean-up required was because the field notes were transferred as a replicate of the paper field data by volunteers who had no experience of the requirements of data integrity required for data analysis. Common problems picked up were "O" instead of 0 (zero), and "I" instead of 1. Sometimes units were included in height measurements (cm or m) and some non-numeric symbols, e.g.," ~" or "/" or"-", the latter two indicating two values within a cell, e.g., 20/45 for height indicating two measures were made within the same quadrat on the same sampling occasion. Sometimes, where "-" was used the data was erroneously encoded automatically as a date record (Oct-40) by EXCEL. Where two values were given, they were replaced by the mean. These issues were few but had to be corrected before the data could be used.

These data were re-structured to produce four worksheets, essentially separating the different components of the database, i.e.:

Worksheet 1, the species dictionary. This worksheet contains the species names and a two-/three-letter abbreviated code. The abbreviated code is useful for producing less-fussy graphical outputs. This process also allowed species nomenclature to be brought up to the most-recent views, e.g. *Deschampsia flexuosa* becomes *Avenella flexuosa* (Stace, 2019). Names of all species detected are presented in the Figure10 legend.

Worksheet 2, the cover data (%) for all vascular plants, bare ground and combined lichens, bog mosses (*Sphagnum*) and other mosses.

Worksheet 3: height data (cm) for *C. vulgaris, Erica cinerea, E. tetralix, Ulex gallii, U. europaeus* plus *Betula* spp. and *Pinus sylvestris*.

Worksheet 4, the VIM data, a categorical three-point scale (V, I, M) for five species: *C. vulgaris, Erica cinerea, E. tetralix, Ulex gallii* and *U. europaeus*. These data are not discussed further here.

The three worksheets containing data all had the same format, this is illustrated in abbreviated form for the 2020 cover dataset in Table 1. Note:

1. The variable names occur as column headings.
2. In 2020 there were 468 rows of data (12 quadrats x 39 years); where data were not collected missing values (coded NA) were included to keep a balanced database
3. Column A is an index number and is useful if you wish to sort and resort data and aids reading data into some statistical packages.
4. Column B is the year of sampling, now 1982 to 2020
5. Column C is elapsed time (coded ET) setting year 1982 to zero for all quadrats, this variable is useful for improving graphical outputs. As of 2020 the range for ET is 0-38.
6. Cols B, C and D (in red) are variables that collectively describe the entire row of data as an unique entity, either as Quadrat No. + Year or as Quadrat No. + ET.

Once the 2011-2019 data were transferred, volunteers transcribed the remaining data (1982-2010) and then a thorough data check was carried out. It took almost 12 months to complete all these tasks, just in time to input the 2020 data. At this point, the dataset was archived with Record, the Local Records Centre for Cheshire (Record, 2020).

The data were now in a format that could be easily "cut and pasted" into proprietary statistical programs such as MINITAB (MINITAB, 2017) or SPSS (SPSS, 2018) or output as tab-delimited (filename.txt) or comma-delimited files (filename.csv) for input as a "data.frame" into the R statistical environment (R Core Team, 2018). Here, all subsequent analyses use the R statistical environment; the beauty of this approach is that (a) R is freeware, and (b) assuming future data are added into the EXCEL worksheets in exactly the same format, the R-scripts written for this paper can automatically re-analyze the combined new dataset.

TABLE 1. Sample of part of the EXCEL Worksheet 2 illustrating part of the species cover data: blue cells reflect the EXCEL columns/row references, yellow cells contain the variable names (species as two-/three-letter codes, green cells contain an internal index number, and the white cells contain the cover data (%). The data in red are the variables that provide unique codings for each data row.

	A	B	C	D	E	F	G	H	I	➔Col AD
		Quadrat No	Year	ET	Cv	Ec	Et	Ug	Mc	
	1	1	1982	0	50	0	0	0	5	
	2	2	1982	0	80	15	0	18	0	
	3	3	1982	0	70	2	0	40	3	
	4	4	1982	0	25	0	15	0	40	
	5	5	1982	0	10	0	45	0	20	
	row 468									

Analyses

Two types of analysis were performed:

1. **Simple graphing**: Here the aim was simply to chart the changes in species abundance, tree height (mean height of both *Betula* spp. and *Pinus sylvestris*) and the Ellenberg N Index through time for each quadrat. The four Ellenberg functional trait indices (L, F, R, N) were calculated for each of the quadrat x year combinations by summing the product of the cover of each species with its respective revised Ellenberg value (corrected for British conditions, Hill *et al*., 2004), following Milligan *et al*. (2016, 2018). The values used to derive our indices were downloaded from (CEH, 2004). Although all four weighted indices were computed, only Ellenberg N is reported here. This is because all indices provided similar responses and N is likely to be a good indicator of deleterious change (Smart *et al*., 2003).

   Initially, graphing was done using the 'ggplot' function in the 'ggplot2' package (Chang, 2018) to plot all 12 quadrats separately within a single lattice plot. The individual points were joined together to show actual changes through time and a non-linear regression (method = "loess") was fitted to highlight possible curvilinear relationships. Other variables can be derived from the cover data.frame as required, for example species richness and various diversity indices using the 'specnumber' and 'diversity' functions within the 'vegan' package (Oksanen *et al*., 2018). To aid discussion here, some plots were produced with a selection of quadrats.

2. **Multivariate analysis**: here all species cover data were analyzed using Detrended Correspondence Analysis (DCA, Hill & Gauch, 1977) using the 'vegan' package (Oksanen *et al*., 2018). DCA was performed using the 'decorana' function to produce an ordination pattern that reflects ecological gradients for both species and quadrats. Here, we used the species cover data which had been Hellinger-transformed using the 'decostand' function in 'vegan'. Species that were only present once were excluded from this analysis. The ordination was then correlated with elapsed time using the 'envfit' function, and 2-dimensional standard deviational ellipses with 95% confidence limits were calculated using the 'ordiellipse' function and overlain on the quadrat plot. The trajectories of each individual quadrat points were then plotted through time. Finally, the distance between the start and end point for each trajectory was calculated by Pythagoras and then rank-ordered; arbitrary thresholds were used to rank the quadrats on a traffic-light system highlighting those quadrats that had moved least and were at least risk (green), intermediate (amber) and those that had moved furthest and may require some management intervention (red).

RESULTS

Simple graphing of species variables

Cover data were available for 36 species (some recorded as seedlings and saplings) plus litter and bare ground. Simple graphs were produced for management purposes of all species but only a few examples are presented here.

Over the entire monitoring period, *C. vulgaris* cover has increased in three quadrats (4,10 and 11) and has been more or less stable in two quadrats (Quadrats 5 and 9) (Figure 3). Two quadrats showed a consistent decline through time (Quadrats 1 and 12) and the remaining quadrats showed greater cover in the earlier stages and a recent decline

(Quadrats 2, 3, 6, 7, 8 and 11) (Figure 3). Quadrat 6 has shown remarkable fluctuations between 1-95% on about an 8 to 12-year period (Figure 3). In the six quadrats where *U. gallii* was present, one showed a recent minor increase (Quadrat 4), two showed fluctuations but with a cover usually <30% but with occasional larger peaks (Quadrats 2,3) and three quadrats showing consistent increases throughout the period to ≥50% (Quadrats 2, 6 and 8) (Figure 4).

Interestingly, lichens were recorded frequently in the early years of this study, but by 2005 only Quadrat 10 retained any, and that has reduced to 0.5% cover in the last two years (Figure 5). Moss cover (nearly all *Hypnum cupressiforme* in the dry- and intermediate-heath quadrats) has on the whole increased (Figure 6).The exceptions are Quadrat 7, where moss was removed when the area was mown to aid regeneration of *C. vulgaris*, and Quadrat 12, where there is increasing shade from a large pine tree. Of particular note were changes in the cover of wet-heath indicators in the damper quadrats (Quadrats 4, 5 and 10). *Erica tetralix* responded differently, but the general pattern is one of greater cover in the early stages and a recent reduction to < 20% cover (Figure 7a). *Molinia caerulea* showed an overall reduction in Quadrats 4 and 10, but cover peaked mid-period in Quadrat 5 followed by a decline (Figure 7b). *Drosera rotundifolia*, present in Quadrats 4 and 5 in the early years at low cover (<6%) has not been detected since year 25 (Quadrat 4) and year 10 (Quadrat 10) (Figure 7c). Bog mosses (mainly *Sphagnum* spp.) were present in Quadrats 4 and 5 and have shown considerable fluctuations, being reduced to <10% between years 10-15, before recovering to a peak followed by a worrying decline (Figure 7d).

Tree invasion is a negative feature of heathland management, so we also produced a graph of the changes in combined mean height of the two invasive tree species (*Betula* spp. and *Pinus* spp.). This allows managers to see at a glance when these tree species were invading and their subsequent performance (Figure 8). The quadrats show three types of response, no invasion (Quadrat 1), some invasion but trees remained at a relatively low height (< 1m, Quadrats 2, 3 4, 7, 8, 9, 10 and 11) and quadrats where tree growth was substantive (> 1m) for at least some of the time period (Quadrats 5, 6, and 12) (Figure 8). Of the three quadrats with the most tree growth, improvements are a result of management; Quadrat 12 had grazing excluded for 18 years and trees have been removed subsequently; Quadrat 5 had one major clearance and Quadrat 6 has had some clearance. Both Quadrats 5 and 6 are on damp heath where tree growth is a particular problem.

In terms of the Ellenberg-N Index, it remained at a relatively low level, i.e., below 250 over the 39 years, although there were occasional spikes in seven of the quadrats (Quadrats 2, 4, 7, 8, 9, 10 and 12) (Figure 9). The exceptions (Quadrats 1, 3, 5, 6 and 11) all showed increases above 250, especially Quadrat 1 which reached over 750 (Figure 9). However, all these quadrats were reducing towards the arbitrary threshold of 250 at the end of the study (Figure 9).

Multivariate analysis

The DCA ordination produced eigenvalues of 0.381, 0.152, 0.117 and 0.127 and gradient lengths of 2.58, 2.00, 1.95 and 1.27 for the first four axes, and they were correlated significantly with elapsed time ($r^2 = 33.3\%$, $P<0.001$). The species ordination (Figure 10) shows *C. vulgaris*, the dominant species near the centre with two underlying gradients. Axis 1 represents a moisture gradient from dry-heath at the left-hand side with *Erica cinerea and Ulex gallii* through to wet-heath on the right-hand side with *Erica tetralix* and *Molinia caerulea* (Figure 7). Axis 2 represents a successional gradient from disturbed, open-ground with *Chamaenerion angustifolium* and *Urtica dioica* at the top of the axis through to scrub-wood communities with *Sorbus aucuparia*, *Pinus sylvestris* and *Quercus* spp. at the bottom (Figure 10).

The positions of the individual quadrats within this ordination space shows three groups;

Group 1: Dry-heaths (Quadrats 1, 2, 3 and 8). The ellipses for these quadrats are located mainly towards the left-hand side of the ordination and are orientated vertically suggesting that there are successional changes towards a woodland community occurring at some point during the time period (Figure 19a).The trajectories confirm this with Quadrat 1 moving the furthest towards a woodland community, but then recovering; the other three quadrats fluctuated around the x-axis with relatively little movement suggesting stability and/or cyclic changes (Figure 10b-e). Note, the biplots produced in Figure 9 are four times the scale of Figures 11 and 12.

Group 2: Intermediate-heaths (Quadrats 6, 7, 9 and 12). These quadrats were more or less centered on the Y-axis but were orientated vertically with approximately half below the x-axis, suggesting successional changes to woodland in a similar manner to the dry-heaths (Figure 12a). Quadrats 6 and 7 moved up and down the ordination but the start and end positions were relatively close (Figure 12b,c), whereas Quadrats 9, 11 and 12 have moved closer to woodland communities Figure 12d-f).

Group 3: Wet-heaths (Quadrats 4, 5 and 10). The ellipses for these heaths were located mostly towards the right-hand side of the ordination and are orientated at about a 30° angle suggesting that most of the fluctuations were not successional towards a woodland community (Figure 13a). This is borne out by the trajectories where Quadrats 4 and 5 both moved along the x-axis with minor vertical fluctuations (Figure 13b,c). Quadrat 10, on the other hand, did show some evidence of a downward trajectory towards woodland, but there has been recent recovery, because of management to remove *Betula* spp. All of these quadrats, however, have moved to drier conditions through time, i.e., a shift to the left through time (Figure 13b-d).

Lastly all twelve quadrats were scored on a traffic-light system based on the distance between the start- and end-points on their respective trajectories (Figure 14); this clearly identified the dry-heath quadrats (Quadrats, 1, 2, 3 and 8) as the 'red' ones, i.e., those that have moved the furthest distance and are hence most likely to require proactive management. The results were less clear-cut between the other groups.

Quadrats 1, 2 and 3 are outside the grazing paddocks, and Quadrat 8, although inside a paddock, remains relatively unaffected by cattle grazing. Of the remaining quadrats, the position of Quadrat 7, noted as least in need of management, reflects to some extent the mowing undertaken in 2015/6, a technique which hopefully can be extended to other areas. Quadrat 10 also had some extensive management by removal of *Betula* spp. Quadrat 9 on very thin soils over sandstone, appears to maintain itself as almost pure *C. vulgaris*. This has increased slightly in height over the decades, but otherwise there was little other change.

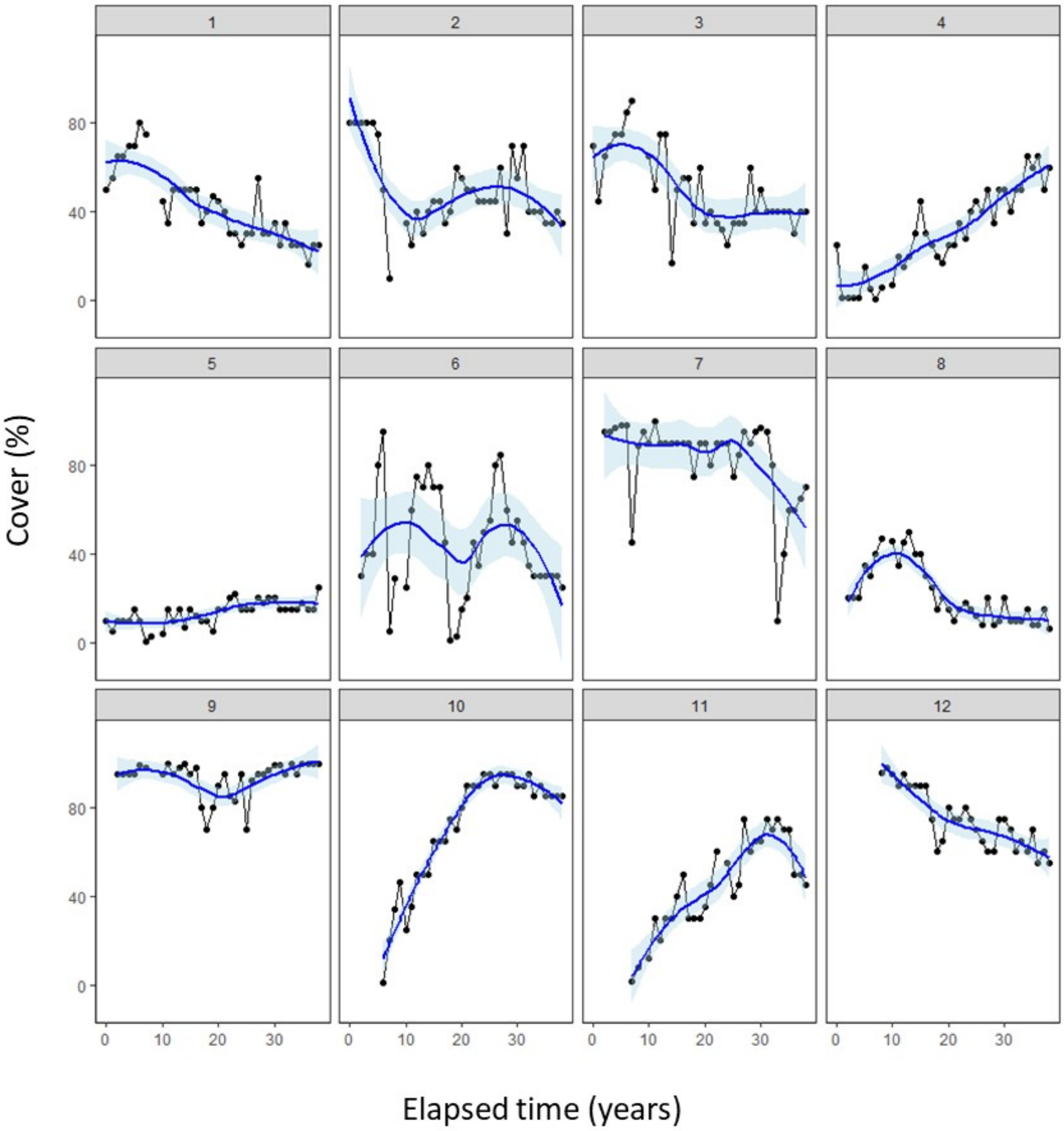

FIGURE 3. Change in *Calluna vulgaris* cover in twelve quadrats on lowland heath at Thurstaston Common, Wirral over a 39-year period (1982-2020). Raw data are plotted along with a fitted non-linear relationship (loess as dark blue line) with 95% confidence limits (light blue).

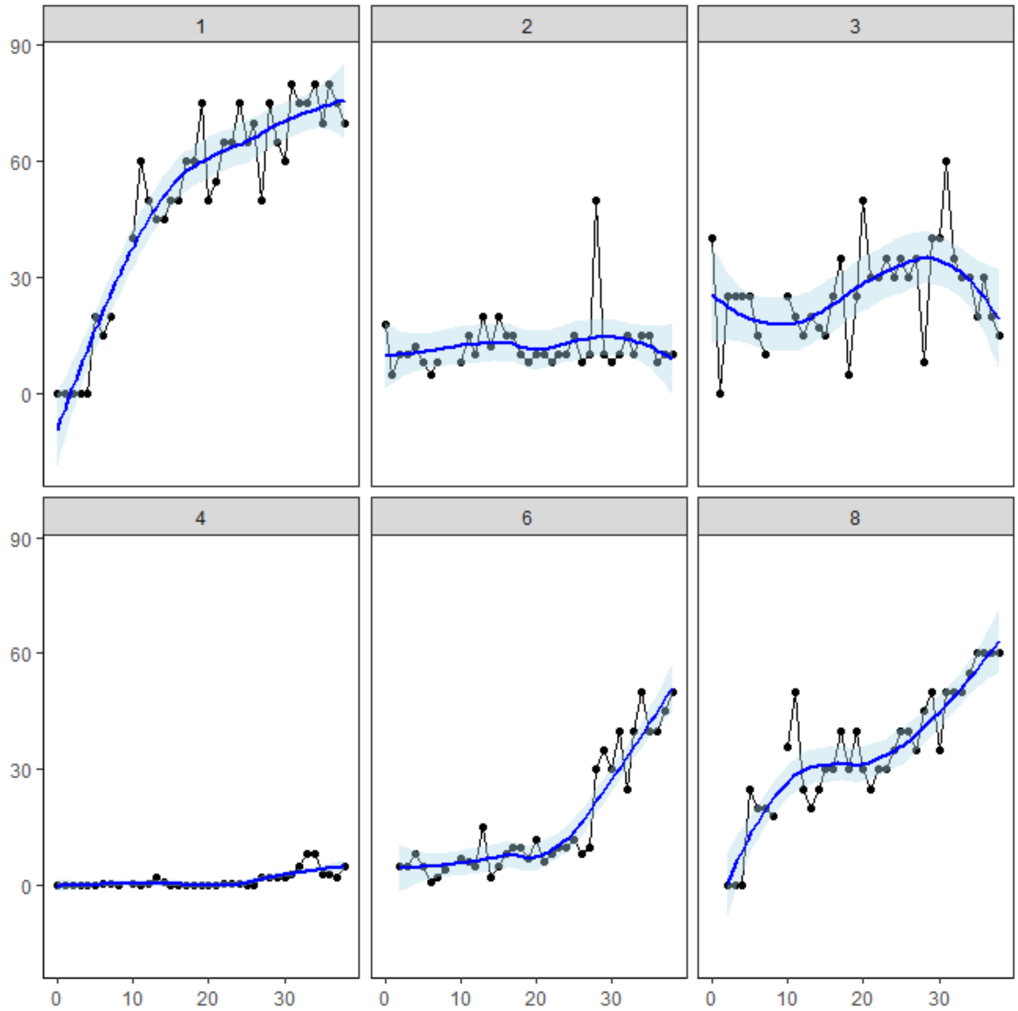

FIGURE 4. Change in *Ulex gallii* cover in dry-heath quadrats on lowland heath at Thurstaston Common, Wirral over a 39-year period (1982-2020). Raw data are plotted along with a fitted non-linear relationship (loess as dark blue line) with 95% confidence limits (light blue).

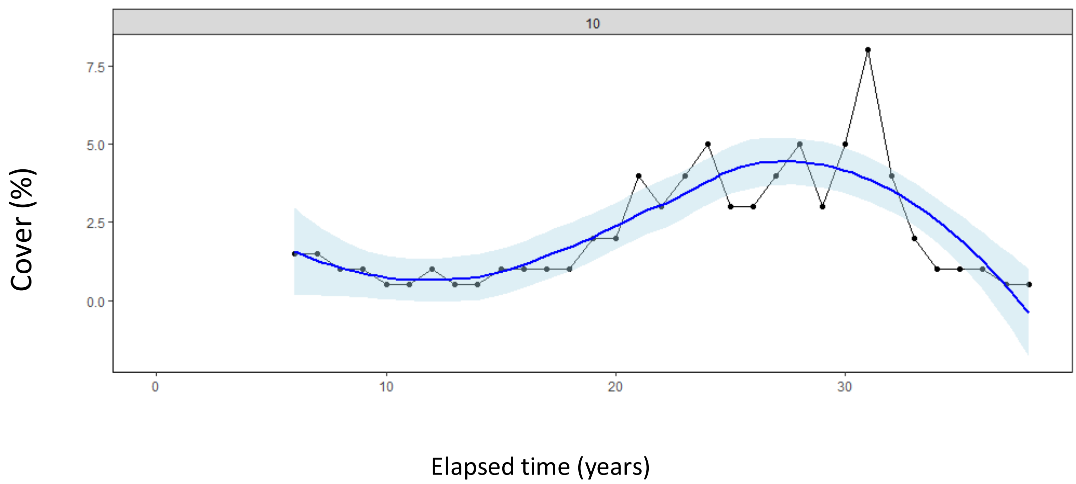

FIGURE 5. Change in lichen cover in Quadrat 10 on lowland heath at Thurstaston Common, Wirral over a 39-year period (1982-2020). Raw data are plotted along with a fitted non-linear relationship (loess as dark blue line) with 95% confidence limits (light blue). Lichens disappeared from all other quadrats by 2005.

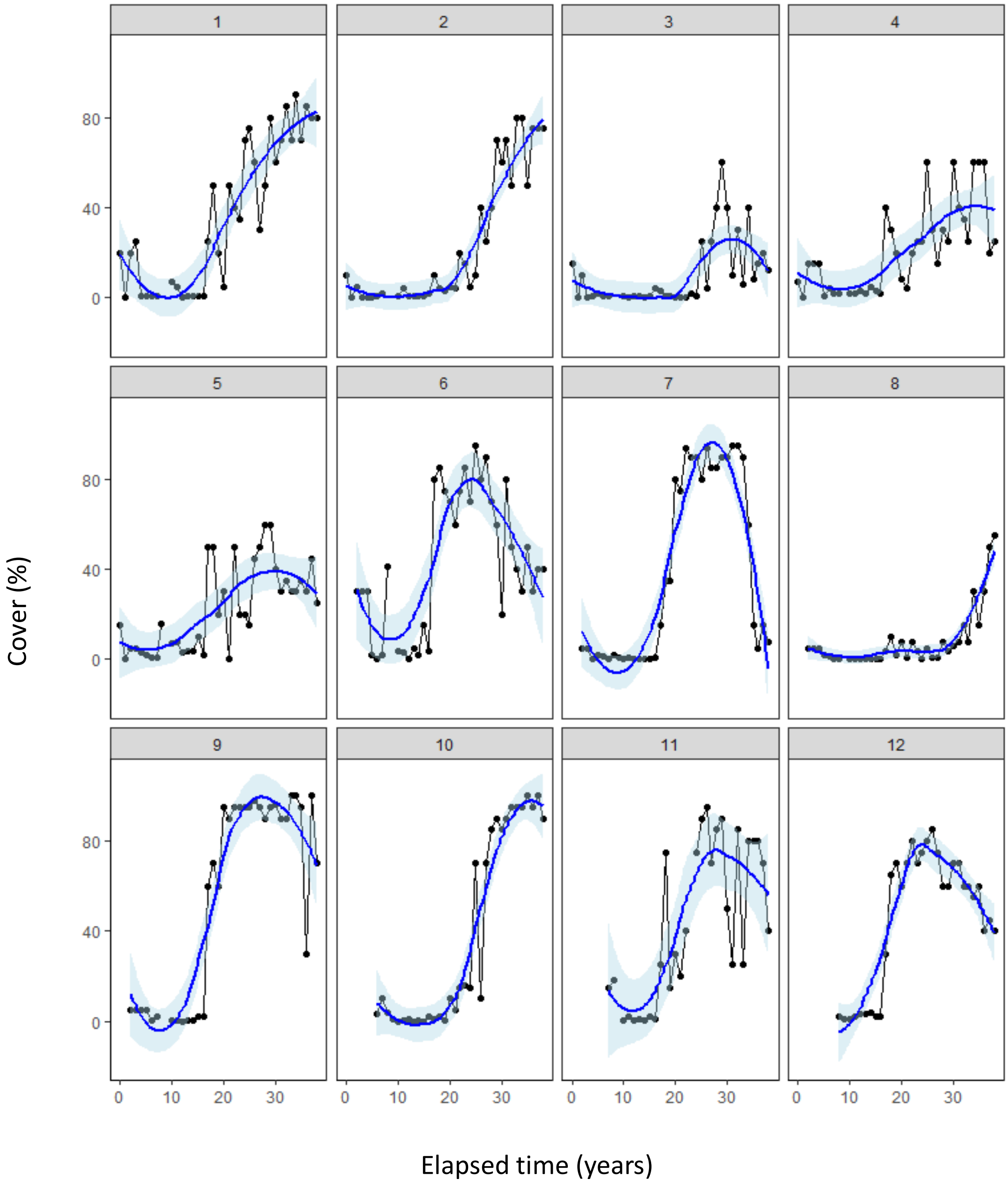

FIGURE 6. Change in moss cover (non-*Sphagnum* mosses) cover in twelve quadrats on lowland heath at Thurstaston Common, Wirral over a 39-year period (1982-2020). Raw data are plotted along with a fitted non-linear relationship (loess as dark blue line) with 95% confidence limits (light blue).

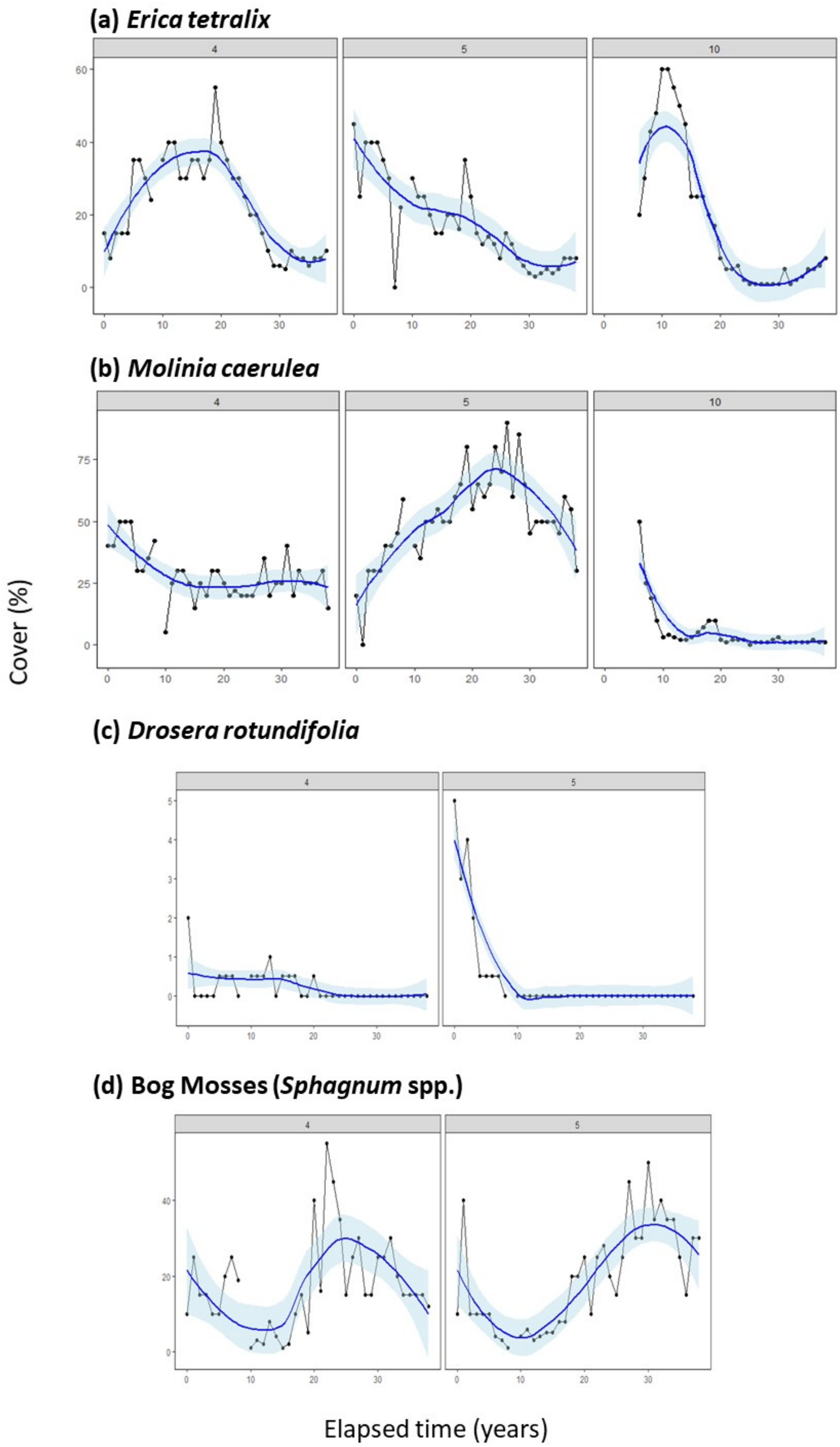

FIGURE 7. Change in cover of three key wetland indicator species (a) *Erica tetralix*, (b) (Bog mosses, mainly *Sphagnum* spp. and *Drosera rotundifolia*) cover in the three wetland quadrats on lowland heath at Thurstaston Common, Wirral over a 39-year period (1982-2020). Raw data are plotted along with a fitted non-linear relationship (loess as dark blue line) with 95% confidence limits (light blue). Note, Bog Mosses and *D. rotundifolia* were not recorded in Quadrat 10.

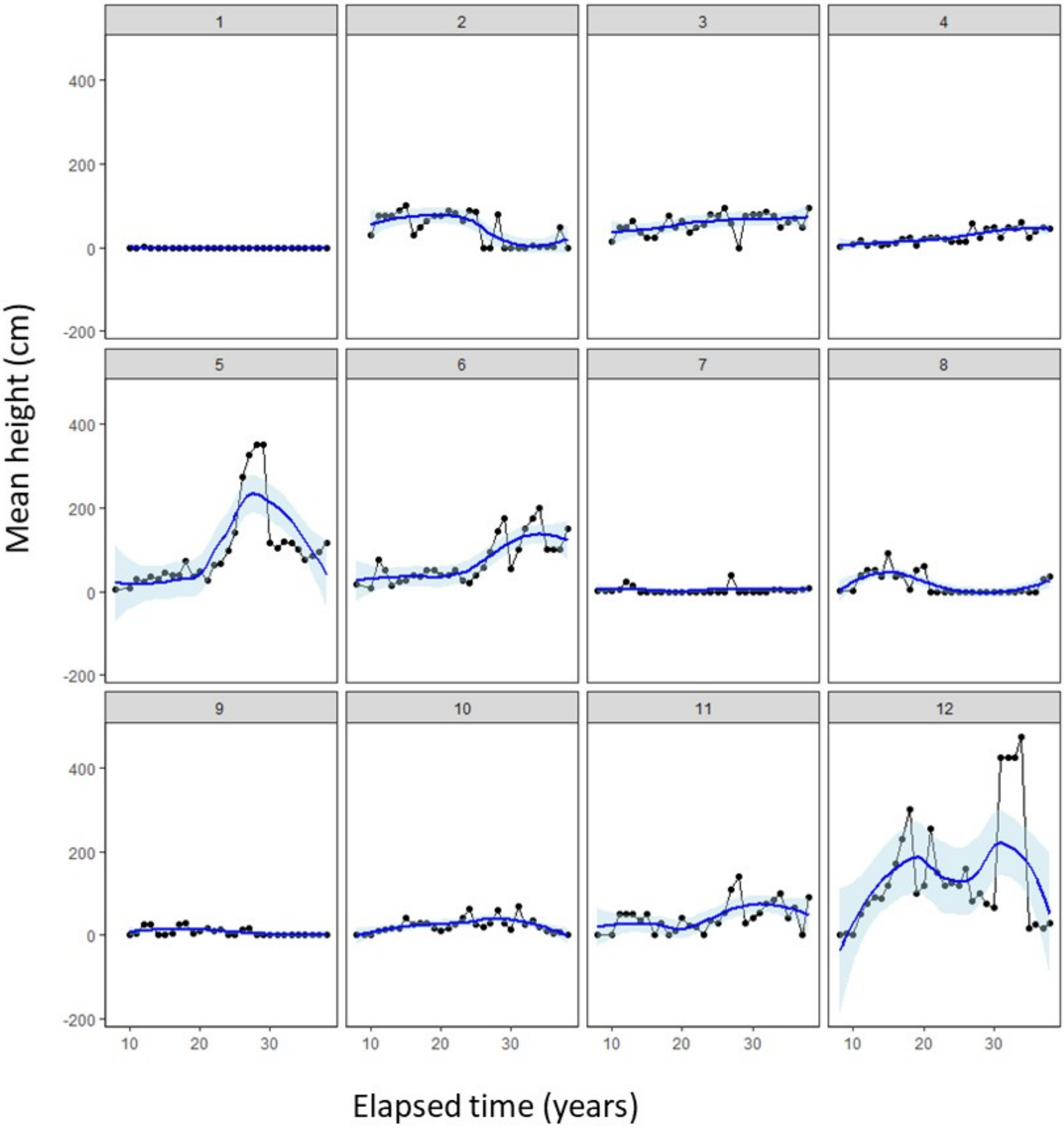

FIGURE 8. Change in the mean height of trees (*Betula* spp. and *Pinus sylvestris*) in twelve quadrats on lowland heath at Thurstaston Common, Wirral over a 39-year period (1990-2020). Raw data are plotted along with a fitted non-linear relationship (loess as dark blue line) with 95% confidence limits (light blue).

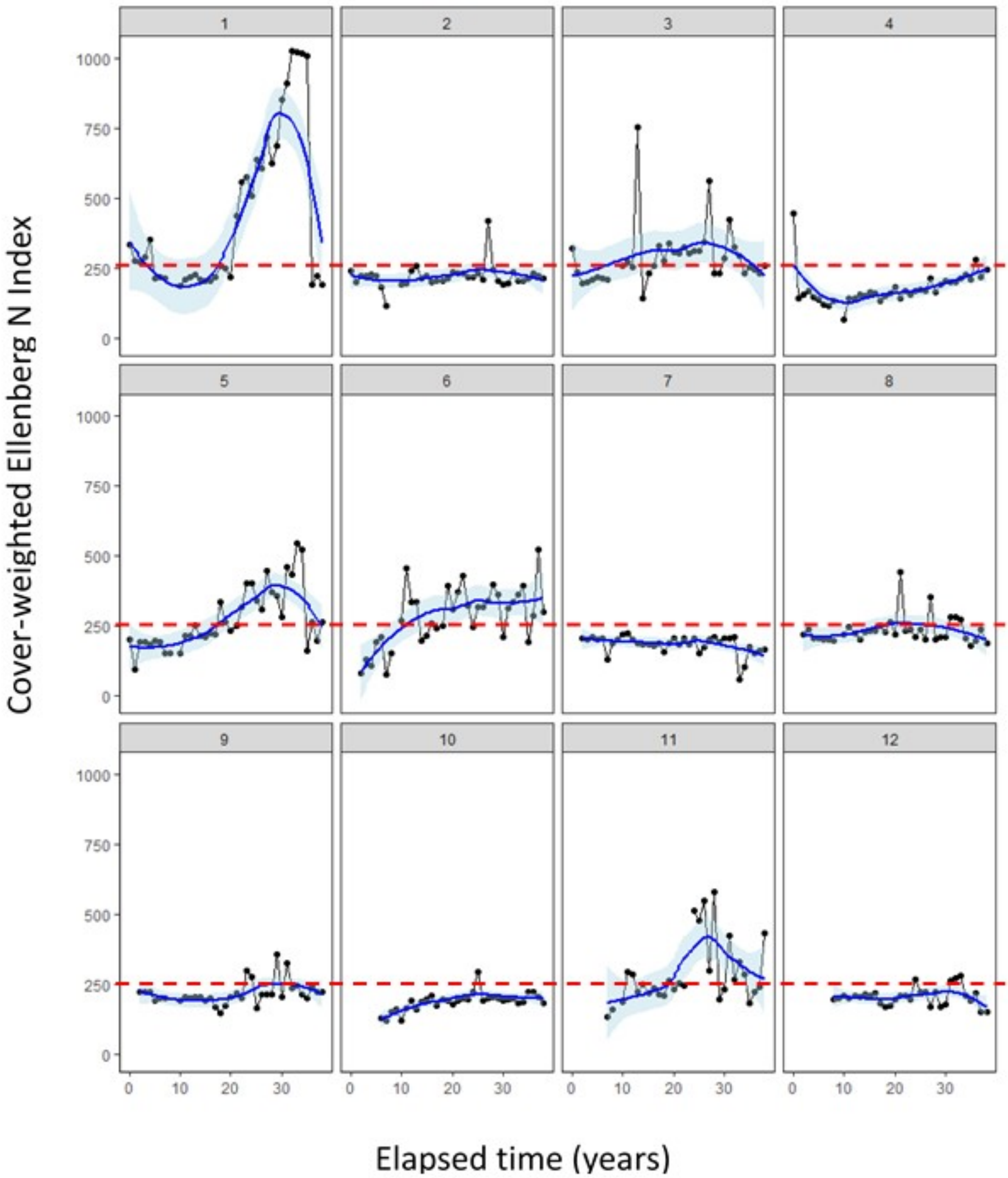

FIGURE 9. Change in the cover-weighted Ellenberg N index in twelve quadrats on lowland heath at Thurstaston Common, Wirral over a 31-year period (1990-2020). Raw data are plotted along with a fitted non-linear relationship (loess as dark blue line) with 95% confidence limits (light blue). The dotted red line is an arbitrary threshold set at 250.

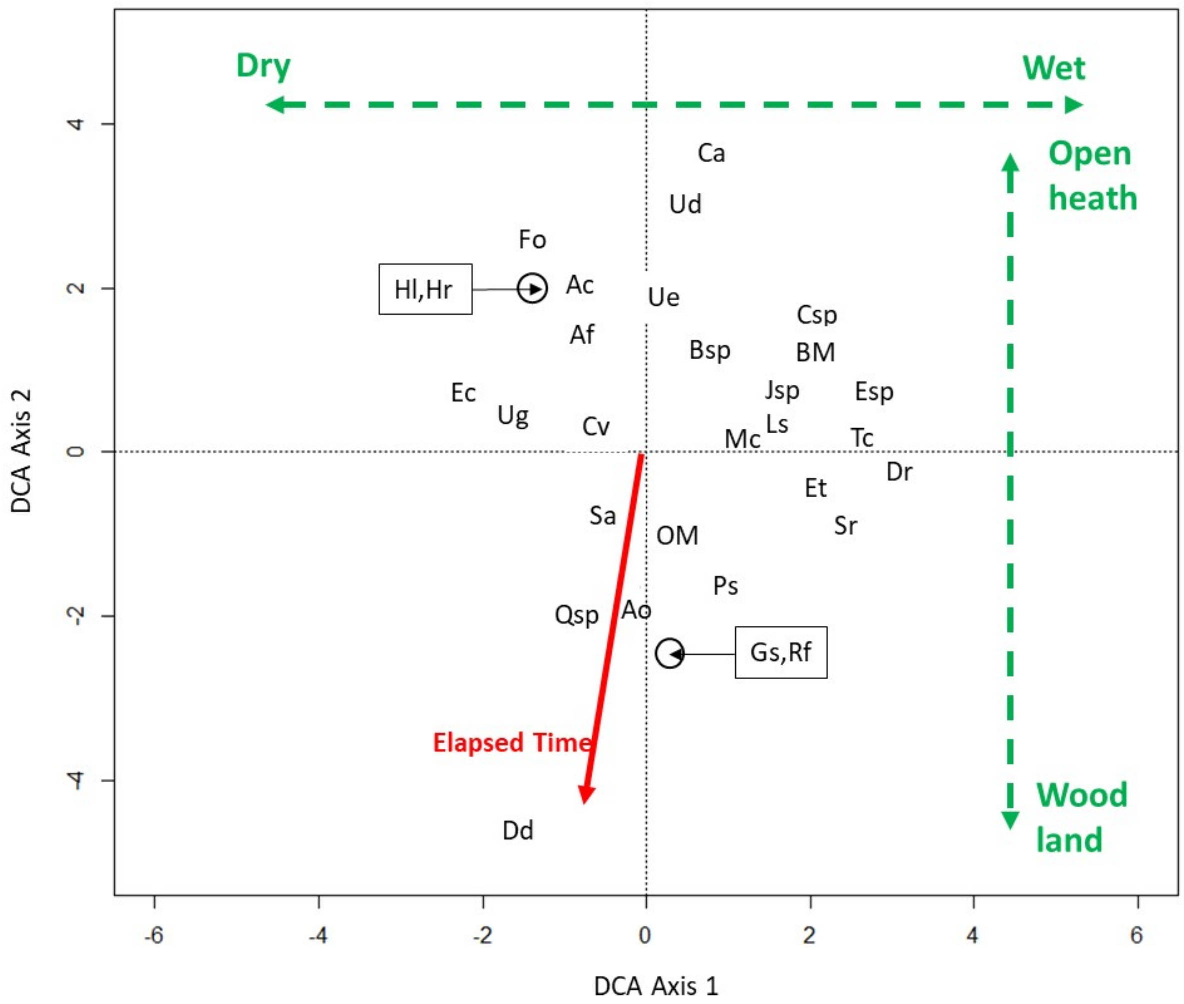

FIGURE 10. Species plot derived from a DCA ordination of 27 years of data from 12 permanent quadrats at Thurstaston Common, Wirral; the vector for elapsed time is also displayed in red along with interpretation of the two major gradients (green-dotted lines). Species key: Ac=*Agrostis capillaris*, Af=*Avenella flexuosa*, Ao=*Anthoxanthum odoratum*, BM=Bog Mosses, Bsp=*Betula* spp., Ca=*Chamaenerion angustifolium*, Csp=*Carex* spp., Cv=*Calluna vulgaris*, Dd=*Dryopteris dilatata*, Dr=*Drosera rotundifolia*, Ec=*Erica cinerea*, Esp=*Eriophorum* spp., Et=*Erica tetralix*, Fo=*Festuca ovina*, Hl=*Holcus lanatus*, Gs=*Galium saxatile* Hr=*Hypochaeris radicata*, Jsp=*Juncus* spp., Ls=*Luzula* spp., Mc=*Molinia caerulea*, OM=Other mosses, Ps=*Pinus sylvestris*, Qsp=*Quercus* spp., Rf=*Rubus fruticosus* agg., Sa=*Sorbus aucuparia*, Sr=*Salix repens*, Tc=*Trichophorum cespitosum*, Ud =*Urtica dioica*, Ue=*Ulex europaeus*, Ug=*Ulex gallii*. Species not included (only one occurrence: unidentified fern spp.).

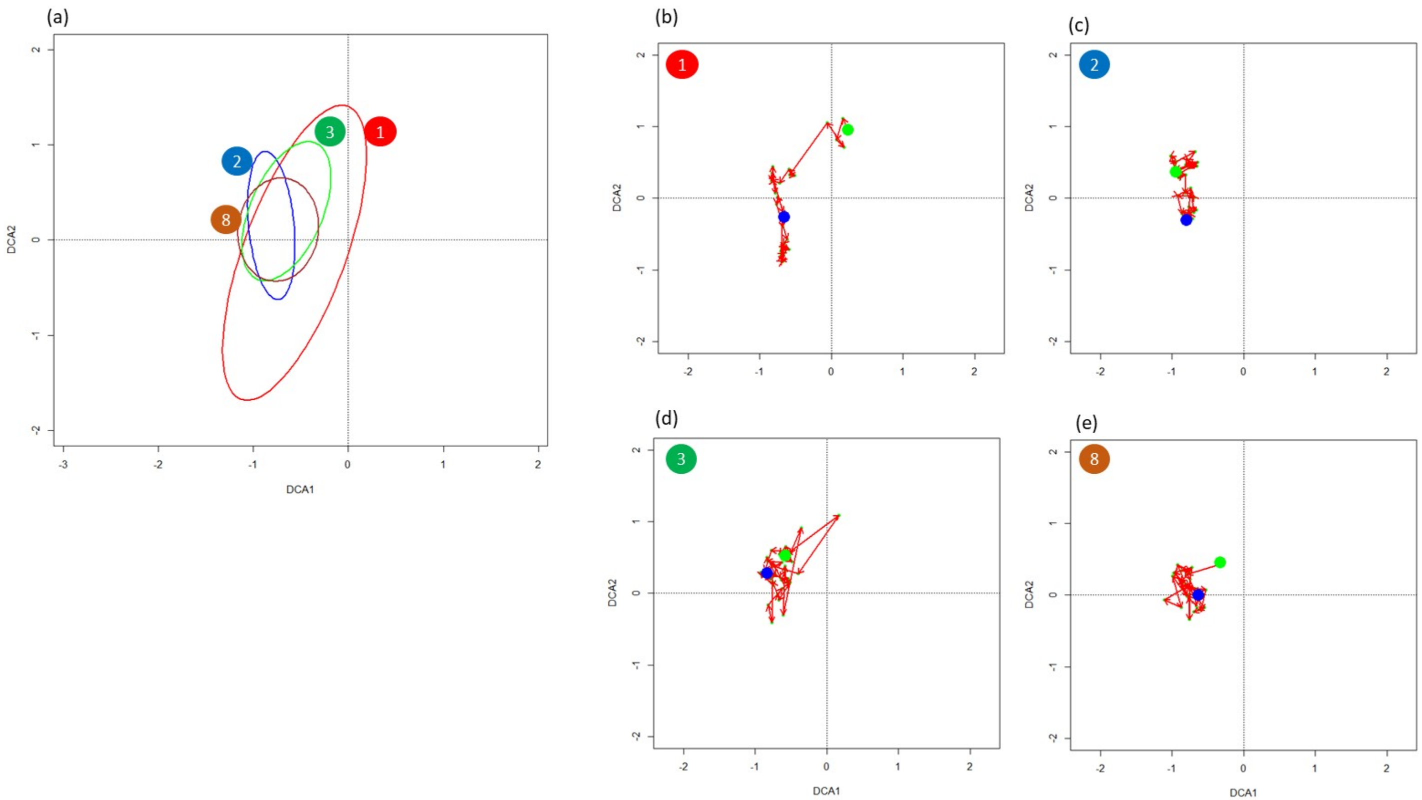

FIGURE 11. Position of the dry-heath quadrats (Quadrats 1, 2, 3 and 8) within the DCA ordination based on 27 years of data from 12 permanent quadrats at Thurstaston Common, Wirral expressed as: (a) 2D standard-deviational ellipses (95%CL) and (b-e) individual quadrat trajectories through time from the start point (green dot) to the end point (blue dot).

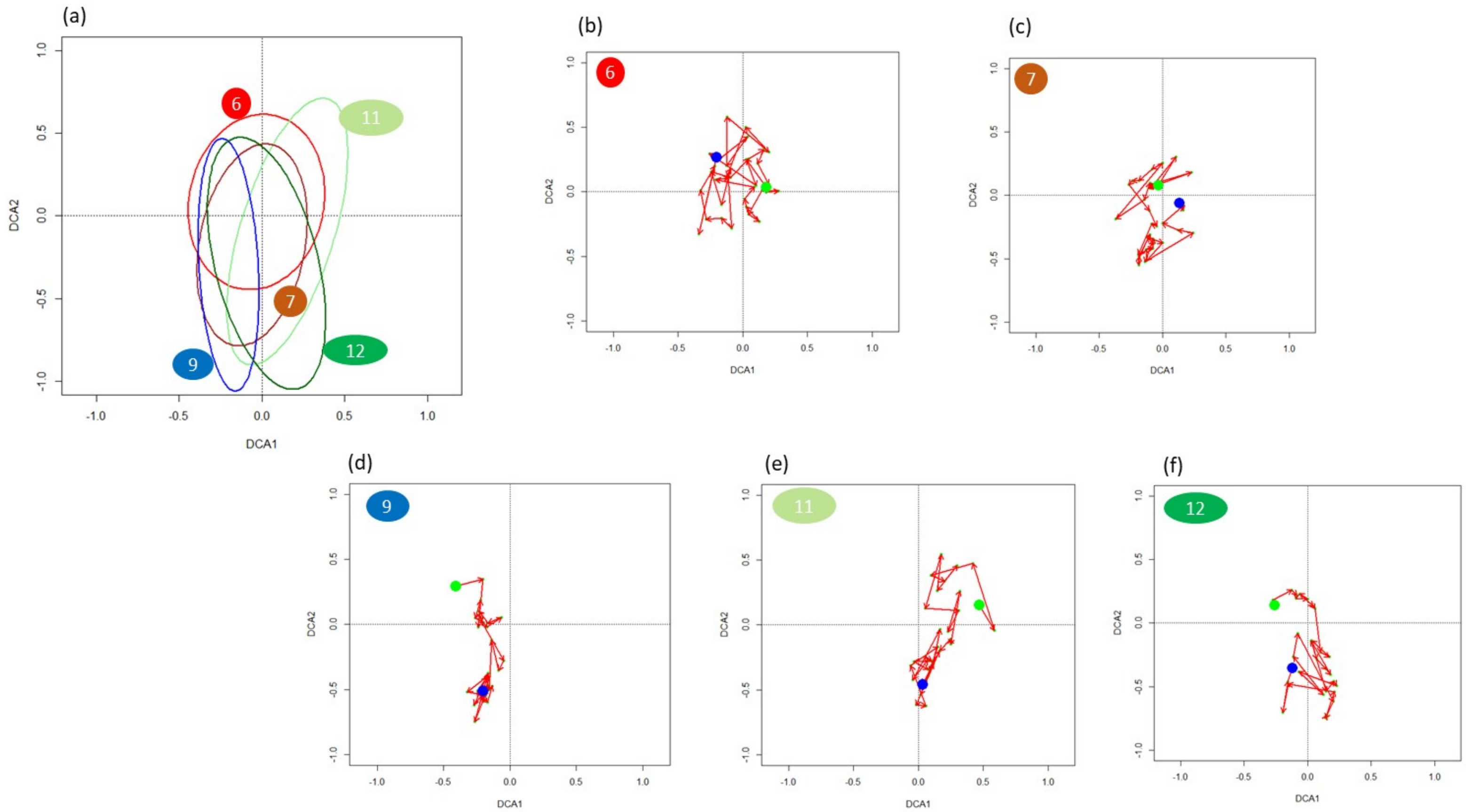

FIGURE 12. Position of the intermediate quadrats (Quadrats 6, 7, 9, 11 and 12) within the DCA ordination based on 27 years of data from 12 permanent quadrats at Thurstaston Common, Wirral expressed as: (a) 2D standard-deviational ellipses (95%CL) and (b-e) individual quadrat trajectories through time from the start point (green dot) to the end point (blue dot).

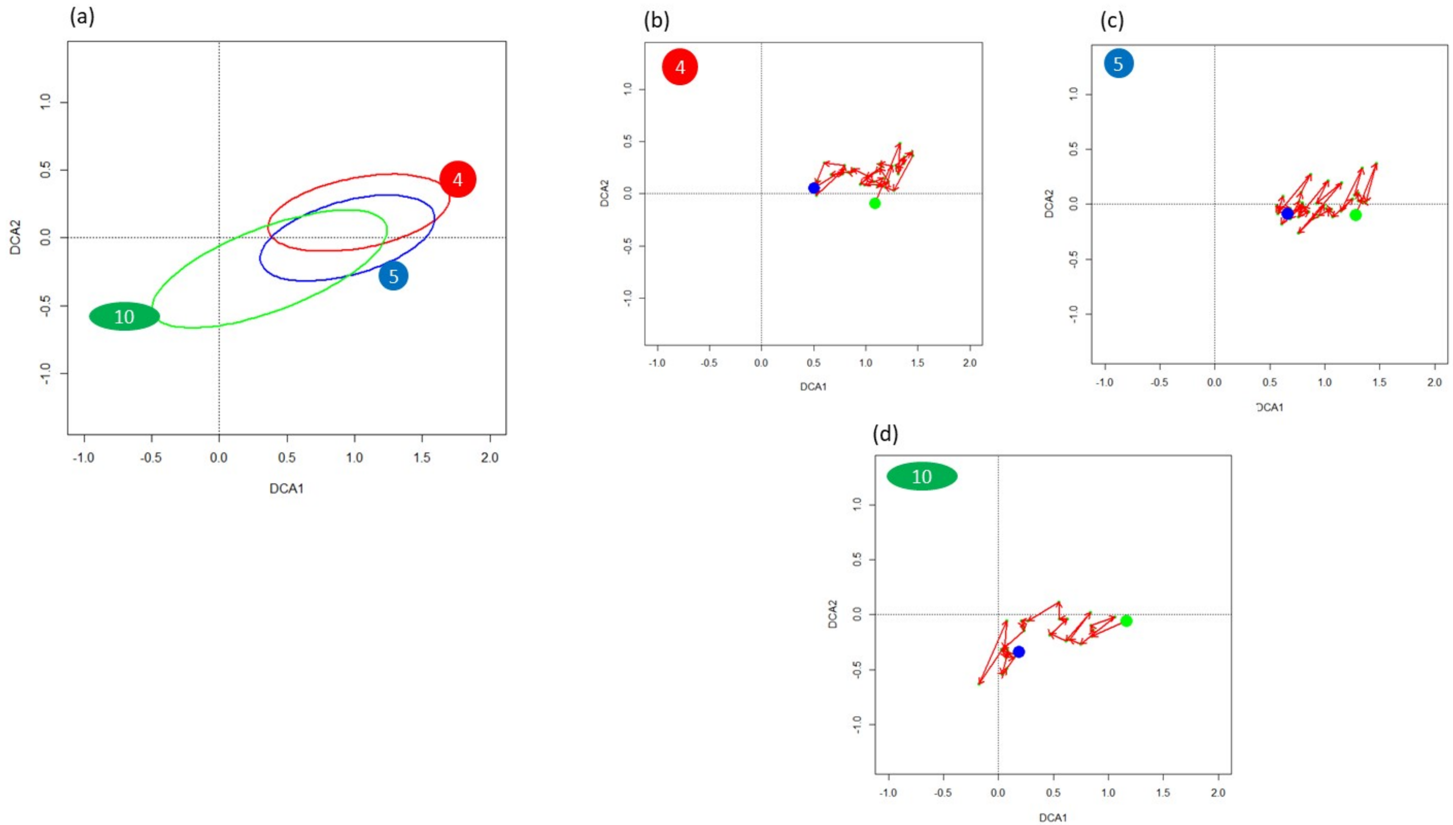

FIGURE 13. Position of the wet-heath quadrats (Quadrats 4, 5 and 10) within the DCA ordination based on 27 years of data from 12 permanent quadrats at Thurstaston Common, Wirral expressed as: (a) 2D standard-deviational ellipses (95%CL) and (b-e) individual quadrat trajectories through time from the start point (green dot) to the end point (blue dot).

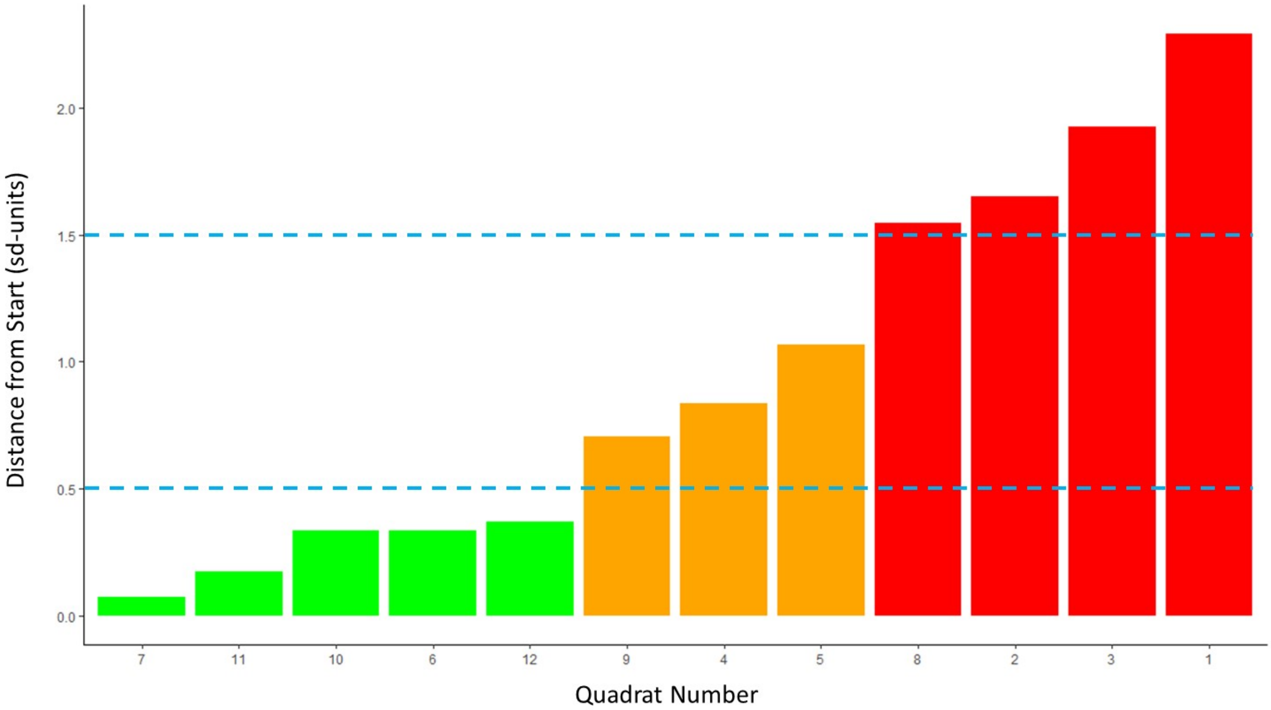

FIGURE 14. The distance in rank-order between the start and end positions of the 12 quadrats within the DCA ordination based on 27 years of data from 12 permanent quadrats at Thurstaston Common. The quadrats have been arbitrarily graded into a traffic-light system (thresholds, blue dashed lines) that highlight the quadrats that may require additional management and those that require least.

DISCUSSION

There are two important reasons to report our results from the monitoring study at Thurstaston Common; first, to illustrate the value of simple monitoring studies generally in conservation practice, and second to illustrate that the results can help guide local conservation management action.

The value of long-term monitoring studies

All ecologists know the value of long-term data. This is championed in the UK through initiatives such as the Environmental Change Network (ECN) and the Ecological Continuity Trust (ECT). The ECN encompasses a range of terrestrial (n=11) and freshwater (n=45) sites where comparable, standardized environmental and ecological measurements have been taken every year for almost 30 years (ECN, 2021). The ECT on the other hand comprise a series of 33 independent studies (as at January 2001), each containing a replicated manipulative experiment (ECT, 2021). Our study at Thurstaston Common is of much smaller scale, of only 12 quadrats, but they have been monitored systematically for 39 years. In global scientific terms they have very limited value because of their small scale, but from a local conservation management point of view, these data are invaluable. We suspect that this sort of monitoring scheme is run by many local organizations/groups involved in nature reserve management, for example Wildlife Trusts, the RSPB and the FSC *inter alia*. Based on our experience with the data from Thurstaston Common we encourage other groups with similar monitoring data to start the process of digitizing their records in a form suitable for modern statistical analysis, if this has not already been done, and to analyze their data.

One reason we charted the transfer of data from field-data sheets to digital form was to illustrate some of the difficulties we encountered and to assist others who may wish to do the same job. One major difficulty was that the field data collectors had no experience of scientific data analysis and hence the field sheets, and indeed their electronic equivalents, were designed for field operations. In this regard they were eminently sensible, but unfortunately the data could not be analyzed in the digitally-stored form. Collating the data, typing the remaining paper-data into digital form, double-checking and indeed triple-checking, and then re-organizing into a usable format for analysis took volunteers approximately 12 months (working at intervals in available time) before the entire dataset was complete. Once this was achieved, however, it was much easier to add in the latest 2020 data. The benefits of this process is that the entire dataset is now held together in electronic format in a single EXCEL workbook, which can be transferred to statistical programs in an analyzable format when required. Here, we have used scripts written for the R statistical environment to analyze these data (R Core Team, 2018), and they can be re-used on an annual basis when new data are added to the database.

In an ideal world, the data collection program should have been planned with data analysis in mind, but it wasn't and it took a great deal of effort to transfer the data to electronic form. We suggest that the custodians of similar, long-term, conservation monitoring data "take the hit" and transfer their data using similar approaches to those described here to enhance the value of their datasets. At the same time, they should also consider developing strategies to pass the monitoring on to others with appropriate training so that the long-term future of the monitoring scheme is safeguarded (Marrs *et al*., 1986).

Guiding conservation action

Realistically, there are two requirements for any conservation management monitoring scheme: (1) a check that the ecosystem being assessed remains in good order and is achieving its conservation objectives, and (2) identification of any untoward changes that may have occurred, which in turn should instigate adaptive management responses to restore the community to an acceptable state. Here, we used a combination of approaches to illustrate potential changes within the heath and communities at Thurstaston Common, concentrating on the use of graphical approaches which illustrate any change very easily to stakeholders, including the reserve managers, volunteers, members of Wirral Wildlife/Cheshire Wildlife Trust, and the general public.

First, we plotted species and other derived variables through time using a lattice display which provided a readily-interpretable assessment of change through time within a single figure. Although we only considered a few variables as examples in this paper, *C. vulgaris* cover, tree species height, and the Ellenberg-N index, similar graphs were prepared for all recorded species, species richness, diversity indices and three other Ellenberg indices. Inspection of these graphs provided an excellent overview of change over the last 39 years at this site.

The *C. vulgaris* cover data separated the quadrats into four groups, where cover was (1) increasing, (2) remaining stable, (3) decreasing throughout or (4) with a marked recent decline. For those quadrats where cover was increasing or remaining stable there is a suggestion that the *C. vulgaris* cycle is operating, and has done so for at least 39 years. Where there has been a decline, it suggests the cycle has been interrupted in some way by either management factors or an increased abundance of other species. The quadrats identified as showing a recent decline may be candidates for additional management. Interestingly, the quadrats with *U. gallii* present suggested that where this species is present it is either stable or increasing. The changes that have been noted on the reserve are summarized along with suggested management actions for `the future in Table 2. The reduction in lichens is a worrying feature of many heathland vegetation monitoring schemes, especially in upland areas (Milligan *et al.*, 2016, 2018) and the increase in *Hypnum* species has also been noted in unburned upland *C. vulgaris* dominated communities on blanket bog (Milligan *et al*., 2018). For the wet-heath quadrats there is evidence of a "drying-out" with reductions in three key indicator species and fluctuating cover of the bog mosses, and a shift towards dry-heath in the multivariate ordination. This is worrying but recent management to maintain wetter conditions through the installation of bunds may help redress this trend. Further monitoring will be needed to assess the effectiveness of this work. Of course, the very nature of the sample-based approach used here will miss rare species that occur sporadically across the Common, i.e., they are below the detection limits of the methodology used. At least four species, *Drosera intermedia*, *Gentiana pneumonanthe, Salix repens* var. *repens* and *Scutellaria mino*r, were recorded in the past, but not recently. *Lythrum portula* would also be included in this group but it was recorded in 2020 after many years' absence by Mr E. Greenwood, so species can re-appear, presumably from the seed bank (Rowell *et al*., 1982). Taken together, these observations suggests that biotic homogenization may be occurring through the loss of rare species (Smart *et al*., 2006).

The tree invasion data separated the quadrats into three groups, one with no detectable invasion, eight quadrats with some invasion but where growth had been restricted to less than 1 m, and three quadrats where tree growth was substantive at greater than 1 m. All of the quadrats with tree invasion represent current to future problems as they indicate potential succession towards woodland, i.e., towards the right side of Figure 1a (Gimingham 1972, 1992; Davies *et al*., 2021). The results show that many of the quadrats have relatively constant tree height (seedlings and saplings) suggesting that current efforts in tree removal are successful, which reflects National Trust's management activity.

The Ellenberg data showed relative stability in seven of the quadrats over the 39 years, but also that five quadrats were highlighted as showing an increase in the N index, suggesting that conditions have become more fertile. This increase in species of more fertile conditions has been noted within the British uplands (Mitchell *et al.*, 2017, 2018), and within the general countryside (Smart *et al*., 2003). That less than half of the quadrats on Thurstaston Common are exhibiting this signal is encouraging; managers should perhaps intensify adoptive management approaches in the other quadrats, for example by introducing either additional cutting or burning management (Marrs, 1988; Gimingham 1992, Davies *at al*., 2021). It might be argued that the increase in *Ulex gallii*, a member of the Fabaceae and a nitrogen fixer would perhaps be the cause of the eutrophication signal. This is possible as it was present in seven of the twelve quadrats and the correlation coefficient (r) between Ellenberg-N and *U.gallii* cover was 0.40 ($P<0.001$) compared to -0.12 ($P<0.01$) for *Calluna vulgaris*. However, *U. gallii* is classified as a species of infertile conditions and has the same Ellenberg N-value (2) as *Calluna vulgaris* (Hill *et al*., 2004)

The individual species graphs do have their limitations, however, as a reduction for example in *C. vulgaris* could be compensated for by an increase in other species typical of the heathland community, for example *Erica cinerea*, *Festuca ovina* and *Ulex gallii* in drier conditions and *E. tetralix* and *Molinia caerulea* in wetter areas (Bannister, 1976; Rodwell, 1991, 1992). This is where multivariate analyses are more useful as they encompass the abundances of all species in a single analysis in relation to environmental gradients (Šmilauer & Lepš, 2014). Our analysis identified two obvious gradients, a moisture one (horizontal) and a successional one (vertical). There were four important outputs:

1. Separation of the quadrats into three "moisture groups", dry, intermediate and wet-heaths.
2. Some of the dry and intermediate-heaths showed some unfavourable successional movement during the study period, but most showed some sign of recovery.
3. The wet-heaths appeared to move to a drier conditions.
4. The traffic light system, which although using internally-generated and rather arbitrary thresholds, separated sites into three classes reflecting the distance between the start- and finish-points within the DCA. These results highlight the dry-heaths as areas of immediate management concern. This approach can of course be criticized as the baseline has been set at the start-point and this point may not reflect high quality heathland.

However, taken together this analysis provides a new approach to augment the local manager's field-based knowledge and help guide the adaptive management strategy needed for the Thurstaston Common heathlands; its value can only be tested through use, and if necessary, revision (Allen *et al*., 2011; Sutherland & Wordley, 2018). The data have been transferred to the local managers on an annual basis, accompanied by a short, written report and a verbal discussion, and this had helped them plan their management strategies. It is hoped that the graphical approaches developed here can help improve this knowledge exchange on the future, and in the transfer of knowledge of change on the site to non-specialists. Overall, the National Trust are to be congratulated on keeping Thurstaston Common in relatively good condition compared to many peri-urban lowland heathlands, and are encouraged to continue the good management.

TABLE 2. Summary comments on change within at Thurstaston Common and proposed management activity.

Quadrat	Comment	Management action
1	Little managed throughout (no grazing or fires, some tree removal) and is now dominated by tall *Ulex gallii*.	Maintain and monitor
4,10	On damp heath, the increase in *C. vulgaris* has been at the expense of plants typical of damp heath, especially *Erica tetralix*, so is showing deleterious long-term change.	NT have installed bunds round the Quadrat 4 area (2015-2016) and removed much birch from uphill of Quadrat 10. Continue and monitor.
12	Fenced to prevent grazing for 18 years; it became overgrown with trees, and is still shaded by a large *P. sylvestris* tree which inhibits *C. vulgaris* growth.	Fence removed so now grazed. Continue and monitor.
3,7	Obvious dips in *C. vulgaris* cover as a result of management, usually quick recovery: Quadrat 7 was mown in 2015, Quadrat 3 was burned in 1996.	Re-apply mowing as necessary and monitor.
6	Dominated by *U. europaeus* and *Betula* spp., fluctuations reflect management to cut these back.	Re-apply mowing as necessary and monitor.
6, 8, 9, 11, 12	Heather beetles outbreaks in 1999-2000 and 2015 (Quadrats 11, 12 only)	Visual effects at the time were considerable, there was little lasting effect on *C. vulgaris* cover.

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Authors' contributions

HA masterminded the continuous sampling and original data storage and has been involved in most of the field recording; AB, BG, MS and MB-S have been involved with the field recording in at least three years, HA, MB-S and RHM transferred and checked the data; RHM performed the data analyses and interpreted the results; and RHM and HA wrote the manuscript. All authors read and approved the final manuscript. We thank Mr Eric Greenwood for helpful comments on this manuscript.

Data Availability

All data are available from rECOrd (2020).

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Supplementary Appendix.

TABLE S1. Example of a field data collection sheet used routinely by volunteers to collect the data in the heathland monitoring scheme at Thurstaston Common, Wirral.

			Thurstaston Common Quadrat Monitoring	18/9/2019 and 27/9/2019																						2019	
			1	1	2	2	3	3	4	4	5	5	6	6	7	7	8	8	9	9	10	10	11	11	12	12	
			Hilary Ash, June Mortazavi, TimGannicliffe, Nathan Thomas , Taylor Lawton																								
Other Species	Quadrat	Cv		25		40		40		50		15		30		65		15		100		85		50		60	C.vul %
Q12 80% shaded by big pine adjacent, height >10m				I		I		V		I		I		v		V		V		I		I/M		I		V	VIM
Sorbus aucuparis seedling # 5cm				70		50		80		40		40		40		25		50		50		40		60		40	Ht
Q11 oak seedling is Q. cerris		Ec				45		35										20									E.cin %
Luzula campestris #,						I		V										I									VIM
Carex sp (yellow-green tight tussock) #						50		70										60									Ht
Galium saxartile #		Et								8		8										6					E.tet %
Rubus fruticosus agg #										V		V										V					VIM
Other mosses Included a little Polytrichum sp.										30		30										30					Ht
		Ug		75		10		20		2				45				60									U.gallii %
Q4 Agrostis capillaris # bare ground=water				V/M		V/I		V		V				I				I									VIM
				120		40		70		20				60				100									Ht
Q5 Ilex aqu #, 4 oak seedlings, at least 1 Quercus c		Mc								30		55		5		15		10		#		1		50		#	Mol.caer %
		Df										#												4		#	Des.flex %
Q6 1 tall pedunculate oak and 1 Q.cerris seedling		Bet				2		10		10		6		30		#		1				#		1		#	Betula sp
						100		100		100		50		200		5		60				15		5		25	Ht
						N		N		Y		Y		N		Y		Y				Y		Y			Seedling/Regen
		bare								4		5		4		15		4						#		10	Bare Gd %
		lichen																				#					Lichens %
		BogM								15		30															Bog Mosses %
		Moss		80		75		20		20		45		40		15		50		100		100		70		45	Oth. Mosses %
		Trich								5		#															Trich.cesp %
		Eriop								2																	Erioph.sp %
		Pinus										1				#										#	Pinus sp
		Ht										140				5										5	Ht
		Regen										N				Y										Y	Regen
		Quer		#		#						#		1				#		#		#		#		#	Quercus sp
		Ht		5		5						5		60				5		5		5		5		5	Ht
		Regen		Y		Y						Y		Y				Y		Y		Y		Y			Regen